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SUMMARY OF RESEARCH
FINAL REPORT

Title: A Study of Time Dependent Response of Ceramic Materials

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Name of principal investigator: John Hemann

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SUMMARY OF RESEARCH

The research accomplishments under this grant were very extensive in the areas of the development of computer software for the design of ceramic materials. Rather than try to summarize all this research I have enclosed research papers and reports which were completed with the funding provided by the grant. These papers and reports are listed below. Additionally a large amount of technology transfer occurred in this project and a significant number of national awards were received.

References

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"Designing Ceramic Components for Durability", Nemeth, N. N., Powers, L. M., Janosik, L. A., and Gyekenyesi, J. P., The American Ceramic Society Bulletin, Vol. 72, No. 12, 1993, pp. 59-69.

"Durability Evaluation of Ceramic Components Using CARES/LIFE", Nemeth, N. N., Powers, L. M., Janosik, L. A., and Gyekenyesi, J. P., ASME/IGTI Gas Turbine Conference, June, 1994, ASME Paper 94-GT-362 and NASA-TM 106475.

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"Measurement and Modeling of Strength Distributions Associated with Grinding Damage", Salem, J. A., Nemeth, N. N., Powers, L. M., and Choi, S. R., Design for Manufacturability of Ceramics and Glasses Symposium, The American Ceramic So7ciety Annual Meeting, April, 1994.

"NASA/CARES Dual-Use Ceramic Technology Spin-off Applications", Janosik, L. A., Gyekenyesi, J. P., Nemeth, N. N., and Powers, L. M., Proceedings of the 32nd Space Congress, April, 1995.

"High Temperature Slow Crack Growth of Si_3N_4 Specimens Subjected to Uniaxial and Biaxial Dynamic Fatigue Loading Conditions", Choi, S. R., Nemeth, N. N., Salem, J. A., Powers, L. M., and Gyekenyesi, J. P., Proceedings of the American Ceramic Society, Cocoa Beach, Jan, 1995.

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"On Stochastic Parallel-Brittle Networks for Modeling Materials", Gasparini, D, Bonacuse, P., Powers, L., Romeo, A., Journal of Engineering Mechanics, Vol. 122, No. 2, 1996, pp. 130-137.

"Fatigue Parameter Estimation Methodology for Power and Paris Crack Growth Laws in Monolithic Ceramic Materials", Gross, B, Powers, L.M., Jadaan, O.M., and Janosik, L. A., NASA-TM 4699, March, 1996.

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Technology Transfer

The primary mission of the NASA-CARES project is to develop and transfer technology for understanding and predicting the complex behavior of brittle ceramic materials. The technology actually transferred to all recipients is the CARES series of integrated design programs for brittle materials and the required user's manuals, documentation, and consulting services. This technology consists of software and expertise in probabilistic design techniques for advanced structural ceramics and brittle materials in general. Designing ceramic components to survive high temperature and stress loading conditions requires specialized knowledge in statistics and fracture mechanics. The capability to design for any component shape and service environment requires extensive numerical computations. These elements have been combined in the CARES series of integrated design programs. The resulting software is a comprehensive design tool for government, industry, and academia that predicts the probability of failure of a ceramic component as a function of its time in service.

Three steps were crucial to successful transfer of CARES technology. The first was to identify and inform potential users of this technology, which was developed in response to a national needs assessment conducted by the government. This was achieved through publications in the technical literature and leading industrial trade publications. The CARES software is coupled to several well-known commercially available programs which solve for the temperature and stress distributions in components (known as finite element analysis, or FEA, soft-ware); therefore, FEA vendor-sponsored catalogs and symposia were also important informational vehicles. In addition, visitation to customer sites provided valuable opportunities for information exchange, consultation, and collaboration. Second, brittle material producer and user industries were targeted, and contact with interested parties was established. A "hot-line" service was created to answer questions about the use and execution of the software. Consultation on solving particular problems of users was also provided, and when needed, software hook-ups, model creation, and subsequent analysis were performed. A priority was placed on fast response to the customer's needs. Third, the specific needs of the customers were identified in an effort to create an appealing program that is easy to use. Furthermore, because of the diversity of computing platforms, the CARES programs utilize a standard computer language that is platform independent. Customers were provided the source code so that alterations could be made to suit individual user-specific needs. Since this software is integrated with popular FEA programs, the user does not have to abandon software that takes years to learn or, alternatively, purchase new and expensive programs. These steps generated good will and enthusiasm among customers who, in turn, referred others or provided additional contacts.

Technology sharing has been occurring since 1986. During the past three years, over 100 companies worldwide have obtained the CARES software, which has unrestricted distribution. The newly developed version of the software, CARES/LIFE, is restricted to domestic distribution for a period of at least two years. CARES/LIFE has been distributed to about 30 U.S. organizations for testing and is in the process of being disseminated to other existing and new customers. The CARES programs are distributed through the NASA Computer Software Management and Information Center (COSMIC), at the University of Georgia.

Although no constraints have significantly hindered the present technology transfer effort, several opportunities to improve the process have been identified. One area that needs particular attention is the remoteness in dealing with a separate distribution entity for all NASA-developed software. The advantage of having a single point of contact for all software is offset by lack of expertise to instruct users, lack of knowledge of the target market, and lack of feedback to the authors from the users. Two possible suggestions for increasing the opportunities for technology sharing include encouraging customers to contact the authors and allowing the authors to market and distribute programs directly.

The CARES series of integrated design programs developed at the NASA-Lewis Research Center's Structural Integrity Branch are funded by DOE and NASA Aeropropulsion programs. The Structural Integrity Branch combines the three disciplines of analytical modeling, mechanical testing, and nondestructive evaluation to understand and predict the behavior of advanced high-temperature materials, particularly brittle ceramic and intermetallic matrix composites.

The nominees for this award perform various functions within the Structural Integrity Branch at the NASA Lewis Research Center. The Branch conducts research in fracture analysis, probabilistic modeling, model validation, brittle materials design, and life prediction code development. The regular job duties for each of the nominees include the following:

- Noel N. Nemeth, Mechanical Engineer (NASA). Performs research and development of CARES and CARES/LIFE software. Provides hot-line service with customers.
- Lynn M. Powers, Research Associate (Cleveland State University). Performs research and development of CARES and CARES/LIFE software. Provides software assistance for customers.
- Lesley A. Janosik, Materials Research Engineer (NASA). Performs research and development of CARES and CARES/LIFE software. Provides customer assistance as needed.
- Jonathan A. Salem, Materials Research Engineer (NASA). Performs overall guidance and coordination in experimental validation of CARES/LIFE design methodology. Performs advocacy, marketing, and materials characterization testing.
- John P. Gyekenyesi, Manager, Structural Integrity Branch (NASA). Performs overall guidance, coordination, marketing, and advocacy of the CARES and CARES/LIFE

projects. Secures all required support and facilities. Surveys customer needs and technology trends.

A number of cooperative efforts have been generated as a result of the willingness to consult with customers. These cooperative technology programs focus on the capabilities and validation of the CARES software and future enhancements. Major organizations that are involved in these collaborative efforts include Department of Energy (DOE), General Electric, Babcox & Wilcox, Solar Turbines Incorporated, Sundstrand Corporation, Allison, and AlliedSignal Corporation.

Recipient/Technology Users: The CARES and CARES/LIFE programs are comprehensive design tools developed for industry, academia, and government. Current customers represent a wide range of interests (from commercial to military) and comprise a variety of industries including aerospace, automotive, electronics, glass, and nuclear. A sampling of recent customers (between April and September 1993) includes the following: The Aerospace Corporation, AlliedSignal Corporation, Allison, Oak Ridge National Laboratory, Ford, General Electric, Intel, the U.S. Navy, Phillips Display Components, Pittsburgh Plate Glass, Solar Turbines Incorporated, Sundstrand Aerospace, Southwest Research Institute, and United Technologies. Within these organizations the ultimate recipients of this software are engineers and material scientists who design parts and evaluate materials, respectively.

User Goals/Size/Ultimate Customers: The number and diversity of organizations associated with this technology means that customers will come from all segments of the nation including governmental, industrial, and academic entities. For example, in some cases, the customer is interested in designing and building only a single component with an assured reliability, such as a mission-critical item for the U.S. military. Other cases deal with mass produced parts for industrial or consumer markets. User organizations range from large multinational corporations to small consulting firms. All of these customers have the common goal of reducing costs by increasing reliability and efficiency through substitution of structural ceramics for metals.

Tangible Benefits (other than publication of results or design): As the only general purpose public domain integrated design program for predicting the reliability of brittle materials in the U.S., CARES has tremendous impact on helping U.S. industrial competitiveness. The CARES probabilistic design methodology is necessary for accurate failure prediction and efficient structural utilization of brittle materials subjected to arbitrary stress states. This technology applies to materials such as glass, graphite, and advanced ceramics including silicon nitride and silicon carbide. Many commercial products such as turbocharger rotors, rocker arm and cam followers, poppet valves, radiant heater tubes, heat exchangers, and prototype ceramic turbines are widely designed using the CARES series of software. In addition, these programs are used to design large infrared transmission windows, glass panels for skyscrapers, computer chips, cathode ray tubes (CRTs), and even ceramic tooth crowns and knee caps. For example, CARES has been used to design ceramic automotive turbocharger wheels at AlliedSignal's Turbocharging and Truck Brake Systems. The reduced rotational inertia of the silicon nitride ceramic compared to a metallic rotor significantly enhances the turbocharger transient performance and reduces emissions. AlliedSignal's effort represents the first design and large scale deployment of ceramic turbochargers in the United States. Over 1700 units have been supplied to Caterpillar Tractor Company for on-highway truck engines and these units together have accumulated a total of over 120 million miles of service. Another example of the use of this technology is ceramic poppet valves for spark ignition engines. These valves have been designed by TRW's Automotive Valve Division, as well as by General Motors, and have been field tested in passenger cars with excellent results. Potential advantages offered by ceramic valves include reduced seat insert and valve guide wear, improved valve train dynamics, increased engine output, and reduced friction loss using lower spring loads. Glass components behave in a similar manner as ceramics and must be designed using reliability evaluation techniques. Phillips Display Components Company has analyzed the possibility of the spontaneous implosion of alkali strontium silicate glass CRTs. CRTs are under a constant static load due to the pressure forces placed on the outside of the evacuated tube. A 68 cm diagonal tube was analyzed with and without an implosion protection band. The implosion protection band reduces the overall stresses in the tube and, in the event of an implosion, also contains the glass particles within the enclosure. Stress analysis showed compressive stresses on the front face and tensile stresses on the sides of the tube. The implosion band reduced the maximum tensile stress by 20%. Reliability analysis performed using CARES showed that the implosion protection band significantly reduced the rate of failure to about 5 failures per 100,000 units. Finally, CARES technology has spun off reliability analysis software development activities in fiber and whisker reinforced ceramics.

Significance of Benefits (present or future): The primary impetus for the development of CARES and CARES/LIFE is to support development of advanced heat engines and related ceramics technology infrastructure. Significant improvements in aerospace and terrestrial propulsion as well as in power generation require revolutionary advances in materials and structures. To achieve these goals, the maturation of a new class of high temperature materials has been identified as a critical national need. Advanced ceramics offer the unique combination of being common inexpensive materials that have a lighter weight and a greater capacity to sustain load at higher use temperatures than metals. The net result of the use of these materials will be more efficient designs that will yield a reduction of emissions and fuel consumption, reduced dependence on foreign suppliers of energy and strategic materials, increased industrial competitiveness, and enhanced national security. Lastly, the software developed and corresponding technology is used by educators to teach probabilistic methods to engineering students. This helps maintain the technical competence of the engineering work force and provides a new perspective on the engineering process.

Technology or Technical Expertise: The CARES and CARES/LIFE software and accompanying documentation were written by the nominees. This required gathering, understanding, and applying in novel ways the research that has taken place in the field over the last 20 years. By compiling the diverse elements of this technology into one package, a comprehensive design program is available for an engineer to simply pick up and use. The resulting software and the expertise of the nominees are available to all interested organizations. This includes maintaining a "hot-line" service, visitation to customer sites, consultation, training, and performing extensive software hook-ups for particular installations. All this is achieved in a timely fashion, giving the customer the highest priority. In addition, manuals extensively describing the technology, the CARES and CARES/LIFE software, and their correct use for reliability analysis have been prepared.

Marketing Efforts: The current marketing strategy includes identifying and informing potential users, education and training, consulting, and active participation in user's projects. Identifying potential customers involves targeting information to the appropriate industries, their trade associations, or professional organizations. Providing the customer prompt service has resulted in many customer referrals, both solicited as well as unsolicited. This "word-of-mouth" approach to advertising has proven quite effective. Targeting the message to the appropriate customer requires publication in the technical literature, trade publications, and software vendor catalogs. Each of these information vehicles requires a tailored message. Technical literature involves reporting results of research, development, and validation. This information is targeted to the informed or expert technology user. Publishing in trade magazines means the message is tailored more for the layman or novice user. This forum is used to educate people about the use and design of ceramics, and to generate enthusiasm and confidence that ceramics will work for many demanding applications. Additional information resources include general engineering and scientific publications, and specific vendor software catalogs. These publications typically include summaries of program descriptions, capabilities, and usage. Education and training are performed either on-site or at the NASA Lewis Research Center installation. The CARES and CARES/LIFE software have also been provided to educational institutions for constructing courses and labs illustrating the failure mechanisms and design with brittle materials. In this case the software gives the student access to sophisticated tools for data analysis. This interaction not only educates students, but also informs them of the availability and capabilities of these programs. Another part of the current marketing effort is to actively participate in a customer's project. This can include consultation on problem solving, providing analysis services, or integrating the software with the particular FEA software available at a given installation. This is a great help to the customer and enables them quick, efficient access to the technology.

Final Results: An illustrative example of the nominees participation in technology transfer regards an Air Force project to design a zinc-selenide infrared transparent window for an experimental aircraft. Assuring that the window would not fracture was crucial to protect the large investment in the window itself, the detection equipment inside the aircraft, and the crew monitoring the equipment while in flight. The window was first designed and manufactured by the Air Force using standard design methods traditionally used for metals. Prior to installation the Air Force obtained the CARES software. The nominees provided training, software hook-up, model debugging, and peer review of the final Air Force report. CARES demonstrated that the large size of the window greatly increased the chance of in-flight failure. Consequently, the window had to be reduced in size. Although the expense to re-size the window was significant, it was more than offset by preventing a likely failure with potential human injury. Another example regards transfer of CARES/LIFE technology to Oak Ridge National Laboratory's High Temperature Materials Laboratory. Services rendered included two site visits for training and presentation to lab management, software hook-up to the COSMOS/M FEA program, model development and reliability analysis of a convective air heater, and preparation of graphical material for utilization by ORNL personnel.

Follow-up: The CARES series of programs are actively maintained and new capabilities are being developed. Users are surveyed regarding the technology and software. They are encouraged to publish and share their results with NASA. Information collected is being used to prepare a booklet of products designed with this technology.

Leverage: CARES and CARES/LIFE have been used to design many different components in many different industries. However, the fact that the software is used in education represents a particularly gratifying application. The good will NASA has generated with this project also presents the positive image of government directly assisting U.S. industrial competitiveness.

New Relationships: Many new relationships have been created between industry and government since CARES and CARES/LIFE have been distributed, and this cooperation is clearly helping the U.S. compete in world markets. Some of the organizations involved in these efforts include Department of Energy (DOE), General Electric, Babcox & Wilcox, Solar Turbines Incorporated, Sundstrand Corporation, Allison, and AlliedSignal Corporation. In addition, numerous requests have been received from competing industries overseas (Europe and the Pacific Rim) with whom technical exchanges have occurred without release of the latest software version.

Awards

1996 Steven V. Szabo Engineering Excellence Award - NASA-Lewis recognition for the CARES/*Life* team for exceptional engineering achievement involving a design methodology and attending software that have enabled significant improvements in assessing integrity and reliability of advanced structural ceramics and brittle material components.

1995 R&D 100 Award - Developing cutting-edge products that have made their way to the commercial marketplace. Annual award given to the 100 most significant technological developments of the past year as determined by a blue ribbon panel of technologists.

'94 NASA Software of the Year Award (co-winner) - First ever Agency wide award for the development and application of computer software. This award has the same prominence as the Inventor of the Year award.

Federal Laboratory Commission (FLC) award for technology transfer - This award is an annual competition involving all of the federal laboratories. This was one of two awarded to NASA Lewis Research Center in 1994.